

Specifications for a “test ion trap” for ion qubit manipulation

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1 General

The ion trap shall conform to the specifications listed below. Some flexibility in certain parameters (noted below) is intended; a finalized design will be determined in consultation with the customer. The intent is to have a single structure fabricated, with multiple copies delivered to various ion trapping groups capable of testing such a device. The trap is expected to have several trapping zones, but is somewhat adaptable in that not all zones would need to be made operational, depending on the user’s particular goals and requirements. Here, a “zone” is a region consisting of a set of electrodes designed for a specific purpose. There are six main types of zone: loading, transporting, junction, separation, gate, and measurement. In practice, some zones may be used for more than one purpose.

1.1 Trap type

The ion trap device is expected to be designed along the lines of a “linear” Paul trap (see for example Refs. [1] - [6]) but contain multiple zones where logic operations can be implemented on individual ions or separate groups of ions such as described in Ref. [7]. The trap should be able to manipulate several ions in at least 6 zones as indicated in Fig. 1.

i) Trap parameters are expected to give center-of-mass oscillation frequencies of ions along the trap axis of at least 5 MHz in zones B, C, E, and F with correspondingly larger frequencies in the radial direction (direction perpendicular to the trap z axis), in order to hold a group of 5 ions to the trap axis. Masses of ions are anticipated to range from 9 u ($^9\text{Be}^+$) to 113 u ($^{113}\text{Cd}^+$).

ii) Several previous experiments have observed the deleterious effects of RF “micromotion” (see e.g., [1]). Therefore, we require electrode structures compatible with the ability to null micromotion in all zones except perhaps for junction and transporting zones. In zones where micromotion is present, it should be

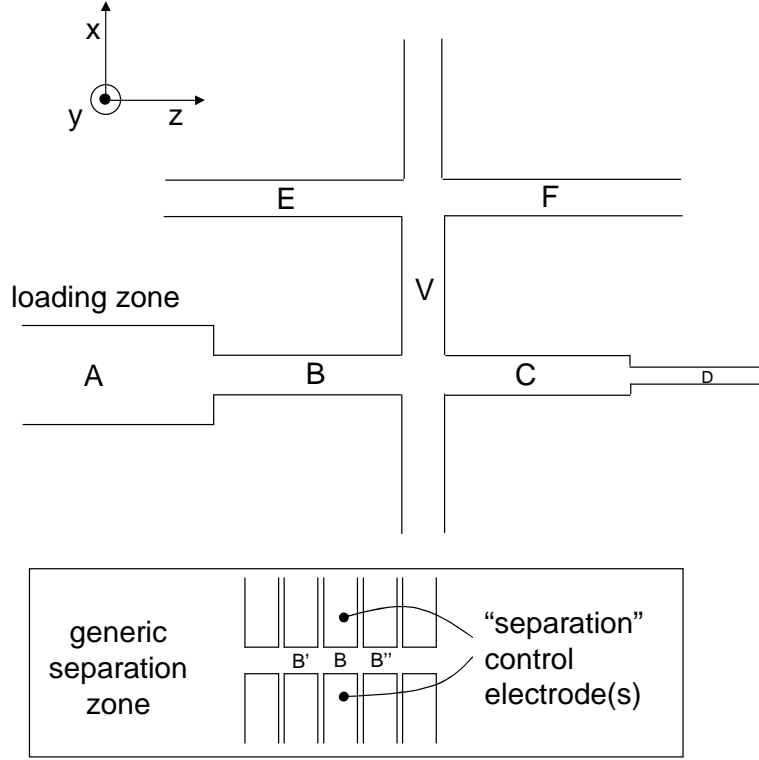


Figure 1: Schematic of the geometry of a 2-D multiplexed test ion trap (individual electrode segments not shown in the main part of the figure). As indicated in the inset at the bottom of the figure, variable potentials are applied to individual “control” electrodes in order to separate and/or move ions for delivery into separate parts of the array (see e.g., [3]). Zone A is a loading zone, zones B, C, D, E, F and V are trapping/transfer zones, zones B, D, and F are separation zones. Zone D has smaller dimensions to be able to test the dependence of ion heating and speed/efficiency of ion separation on the distance between the ions and nearby electrode surfaces.

specified.

iii) It is expected that the trap structure will be provided in assembled form except for user-supplied vacuum hardware and electrical leads to contact pads. A robust mounting structure must be incorporated. At a minimum, this may take the form of a “tongue” with small holes to fix to the user’s apparatus but a “chip-carrier” mounting structure may be more desirable for ease in mounting and replacing individual trap arrays.

1.2 Trap materials

i) Insulating materials used to isolate the individual trap electrodes (1) must be able to withstand the required RF and control electrode potential differences without electrical breakdown and (2) must have sufficiently low electrical loss that the trap temperature does not rise significantly (more than 25° C). It is also desirable to use materials resistant to photoemission and photoionization, since stray charges on electrode or insulating surfaces can affect the stability of the trapping potentials.

ii) Electrode materials must have high-enough electrical conductance to prevent RF loss and heating. RF currents can be estimated from the design values of RF potential and the capacitance between the RF electrode(s) and relevant RF-grounded electrodes.

iii) Consideration must be given to the magnetic properties of the trap materials. It is highly desirable to maintain a uniform magnetic field over the entire processor. Therefore, it may be necessary to avoid all magnetic materials. An estimate must be given of the magnetic field inhomogeneity over the array in nominal fields of 10^{-4} T and 0.1 T.

1.3 Compatibility with scaling

The primary task will be to fabricate a prototype trap electrode structure with the capabilities outlined in Sec. 1.1 that can be tested by the relevant experimental ion trap groups. However, preference will be given to designs that will be scalable to large size (100 – 200 qubits). Therefore, proposals should include discussion of future capability to manipulate/switch many laser beams and electrode potentials, and perhaps incorporate “on-chip” active electronics.

1.4 Multiplexing

The trap should be capable of separating individual ions from (groups of) other ions and moving ions between separate zones. Separation speed is expected to be important in the multiplexing scheme of [7] but not as important in the scheme of [8]. Separation and movement of ions will likely be accompanied by heating, which should be minimized. In current experiments, this has been estimated using classical simulations.

1.5 Vacuum

The trap structure must be high-vacuum compatible and capable of operating at room temperature; typical conditions are total pressure $< 10^{-9}$ Pa (0.75×10^{-11} Torr). This usually means being able to vacuum-bake at temperatures of at least 250° C.

1.6 Implementation of laser cooling and logic gates

Laser cooling and logic gates will be implemented with laser beams focussed onto the ions. All laser beams and associated hardware will be supplied by the user.

i) It is required that the laser beams will not cause excessive detected background light, which might interfere with qubit state detection (see below). In the future, it is anticipated that coherent laser beam manipulations in one zone of the processor will be performed simultaneously with detection in other zones of the processor. It is probably desirable to keep the light from directly contacting electrode surfaces or

insulators near the trapping zone to prevent charging caused by e.g., photo-emission.

ii) In zones B - F, laser cooling must be applied to all ion motional normal modes. Logic gates will be most sensitive to motion along the effective k-vector of the beams [1]; however, it is expected that Doppler cooling must be applied to all modes. This implies that the Doppler laser beam direction must have an appreciable overlap with principal axes of all normal modes, which will depend on trap electrode geometry.

iii) Laser beam access: For each trapping zone we require laser beam access in the y-z plane for directions between $\frac{1}{\sqrt{2}}(-\hat{y} + \hat{z})$ and $\frac{1}{\sqrt{2}}(-\hat{y} - \hat{z})$ (re: Fig. 1) or in the x-z plane for directions between $\frac{1}{\sqrt{2}}(\hat{x} + \hat{z})$ and $\frac{1}{\sqrt{2}}(\hat{x} - \hat{z})$ (most appropriate for a planar electrode structure). A future large-scale structure must incorporate the ability to also control the polarizations of the laser beams.

1.7 Detection of ions

It is assumed that ion qubits will be detected by state-dependent laser scattering. Therefore, clear access for fluorescence detection must be provided. Fluorescence collection optics will be provided by the user, but it is expected that, in zones A, B, C, E, and F, access will be provided to allow use of F1 collection optics with an object distance as small as 2 cm. Specifically, for fluorescence collection, the trap structure must allow placement of a vacuum window (for F1 optics) as close as 2 cm.

2 Trap lay-out

The required general trap configuration is shown in Fig. 1. It should incorporate a loading zone A and trapping zones B - F with variable dimensions in order to test motional heating and ion separation vs. the distance between the ion(s) and the nearest electrode surface. The electrode geometry (e.g., two layer vs. three layer) need not be constant over the array.

i) For a multi-layer structure, the distance between the electrodes in the y direction (out of the plane of Fig. 1) can be held fixed over the array; the variations of distance from the ions to the nearest electrode surface can be determined by the electrode spacings in the x and z directions.

Insulating material should be kept much farther away from the ions than any conducting electrode surfaces, or shielded from the ions. Evidence from several experiments is consistent with stray charge being supported on insulating surfaces. This stray charge can change over long time scales (> 1 s) causing problematic drifts in trap potentials. Therefore, in the example shown in Fig. 2 it is required that $h \gg g$ in order to shield the ions from charges that may reside on the insulators.

ii) Trapping zones: We require separate trapping zones in locations denoted by capital letters A through F. (In the top part of Fig. 1, the individual “control” electrodes are not shown.) The spacing between zones in the z direction is not critical but the distance from any trapping zone to a location where the

spacing of the electrodes in the x and/or y direction changes, or the distance from a trapping zone to a cross, shall be at least three times the distance between the ion and the nearest electrode. In each trapping zone, it is highly desirable that RF electric fields be perpendicular to the trap axis (at the location of the trap axis) to minimize micromotion (achieved by having electrode surfaces parallel to z for example). There shall be enough control electrodes that ions can be located independently in any of the zones simultaneously. The design must include the capability to transport ions between any two zones. The transitions between trapping zones with different widths need not be abrupt as shown in Fig. 1.

iii) Separation Zones: Zones B, D and F are separation zones [3, 4]. We require the width of the separation electrode(s) to be between $1/3$ and 1 times the distance between the ion and separation electrode. In these zones, we also require that there be enough control electrodes so that after separation, the two groups of ions can be located in adjacent zones separated by a potential applied to the separation electrode(s). In the lower inset of Fig. 1, these zones are represented schematically and denoted by prime and double-primed letters. The widths of the additional electrodes do not need to be the same as the separation electrodes.

iv) Trap lateral dimensions: For each trapping zone we specify the distance from the trap axis (where the ions reside) to the nearest control electrode. Tolerances are $\pm 15\%$. It is required that the electrodes be constructed in a way to avoid RF micromotion along the axis.

Zone A: $200\ \mu\text{m}$. The dimensions of this loading trap and its distance from zone B, will be finalized in consultation with the customer.

Zones B, C, E, F: $100\ \mu\text{m}$

Zone D: $70\ \mu\text{m}$

Vertical tracks (zone V in Fig. 1): $100\ \mu\text{m}$

v) The two regions of intersection shown as “crosses” in Fig. 1 can be “T’s” or some other configuration if desired.

2.1 Electrical connections

i) Robust contact pads for user-configured electrical lead-in wires must be incorporated.

ii) We require that the RF electrodes will be joined together so that a single connection can be made to a user-supplied external RF lead.

iii) Contact pads for all control electrodes should be isolated as much as possible from the contact pad for the RF electrodes.

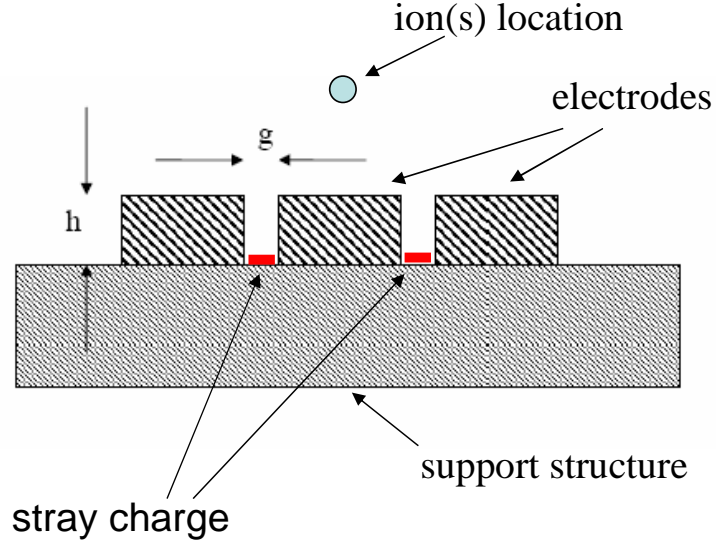


Figure 2: Schematic cross section of electrode structures for the example of a planar trap (see Fig. 4.) For good isolation from stray charges on insulating surfaces, we require $h \gg g$.

iv) Control electrodes should have user-defined low-pass filtering components as close as possible to trapping regions, perhaps on a separately mounted board. The final configuration for low-pass filtering will be determined in consultation with the customer.

2.2 Example electrode configurations

Some possible electrode geometries are indicated in Figs. 3 and 4 and in Refs. [1] -[6].

References

- [1] D. J. Wineland *et al.*, J. Res. Nat. Inst. Stand. Tech. **103**, 259 (1998).
- [2] M. G. Raizen *et al.*, Phys. Rev. A **45**, 6493 (1993).
- [3] M. A. Rowe *et al.*, Quant. Inform. Comp. **2**, 257 (2002).
- [4] J. P. Home and A. M. Steane, preprint (2004).
- [5] J. J. Madsen *et al.*, Appl. Phys. B **78**, 639 (2004).
- [6] L. Deslauriers *et al.*, quant-ph/0404142 (2004).
- [7] D. Kielpinski, C. Monroe, and D. J. Wineland, Nature **417**, 709 (2002).
- [8] L. M. Duan, B. B. Blinov, D. L. Moehring, and C. Monroe, Quant. Inform. Comp. **4**, 165 (2004).
- [9] Q. A. Turchette *et al.*, Phys. Rev. A **61**, 063418 (2000).

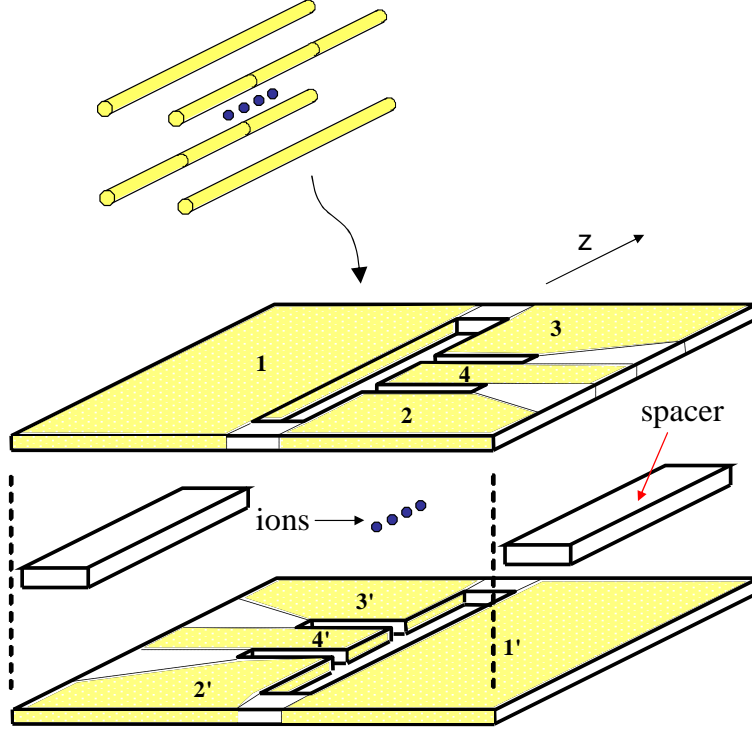


Figure 3: Schematic diagram of a single-zone “two-layer” trap geometry used in Refs. [3] and [9]. The metal plating (shaded) on the cuts in the insulating plates (alumina) were intended to mimic the inner surfaces of the linear quadrupole structure shown in the upper part of the figure. The RF potential is applied to electrodes 1 and 1’; control electrodes 2, 2’, 3, and 3’ are held at a higher potential than control electrodes 4 and 4’ to confine (positive) ions in a static potential along the z direction in a location defined by electrodes 4 and 4’.

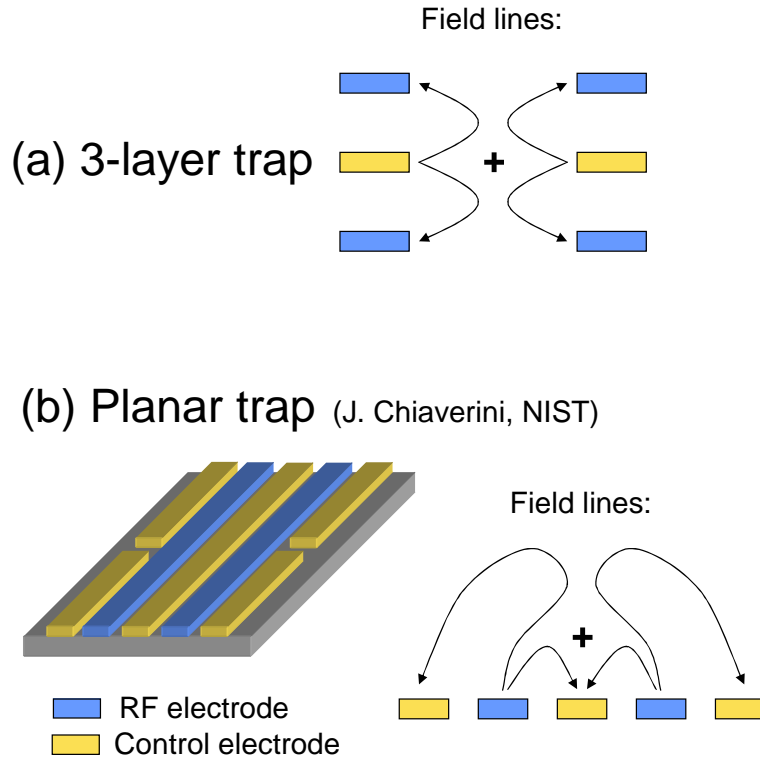


Figure 4: (a) Schematic representation of a possible 3-layer geometry, looking along the z direction or axis of the trap [7, 6]. Here, the RF potential could be applied to the two inner electrodes or the four outer electrodes. (b) Possible planar trap geometry. The RF and control electrode potentials could be switched if desired.